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Parameter Uncertainty in Shallow Rainfall-Triggered Landslide Modeling at Basin Scale: a Probabilistic Approach

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Abstract

This study proposes a methodology to account for the uncertainty of hydrological and mechanical parameters in coupled distributed hydrological-stability models for shallow landslide assessment. A probabilistic approach was implemented in an existing eco-hydrological and landslide model by randomizing soil cohesion, friction angle and soil retention parameters. The model estimates the probability of failure through an assumed theoretical Factor of Safety (FS) distribution, conditioned on soil moisture content. The time-dependent and spatially distributed FS statistics are approximated by the First Order Second Moment (FOSM) method. The model was applied to the Rio Mameyes Basin, located in the Luquillo Experimental Forest in Puerto Rico.

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Keywords: Rainfall-Triggered Landslides; Hydrological Modeling; Uncertainty; Probability.

1. Introduction

The use of coupled distributed hydrological-stability models for shallow landslide hazard assessment at catchment scale is common in the literature. The practice is to utilize the basin hydrological response, evaluated in terms of soil moisture and groundwater fields, to assess a spatially distributed Factor of Safety (FS) by using the

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infinite slope model[1,2,3,4,5]. Mechanical and hydrological soil properties play a crucial role in such an evaluation, and the importance of appropriately modeling soil water dynamics has been clearly demonstrated in some studies[6,7].

The inability to fully characterize hydrological and geotechnical behavior of soil may have a significant impact on model results. Spatial variation of parameters is difficult to describe accurately, and measurement errors can also increase the natural variability of parameters. To account for this uncertainty, FS can be computed within a probabilistic framework, by considering soil parameters as random variables and thus, assigning them probability distributions instead of deterministic values. This practice has received considerable attention in the geotechnical engineering literature, which proposes different methodologies for modeling and analyzing the uncertainty related to the shear strength parameters (i.e. soil cohesion and friction angle) at hillslope scale[8,9,10]. Based on similar approaches, some studies have been conducted for basin scale applications within coupled hydrological-stability models[5,11,12,13]; in such applications, the probability of FS, conditioned to the soil moisture, is dynamically estimated across the basin, whereas the probability distributions of the shear strength parameters are time independent. However, the uncertainty of soil hydrological properties, which may be predominant in case of unsaturated conditions, is still neglected in most published literature. In particular, soil retention curve parameters are the most significant in determining the contribution of the soil matric suction to the equilibrium.

The probability distribution of FS can be derived numerically, analytically or through analytical approximations. The Monte Carlo simulation method uses independent sets of soil properties, generated through a priori assigned probability distributions[8,10] at fixed topographic (i.e. slope) and hydrological (i.e. soil moisture) conditions to obtain a solution. However, such an approach may have significant computational cost for basin scale applications, since the above mentioned conditions change in time and space. The FS probability distribution can be analytically derived in the case where solely geotechnical parameters (i.e., cohesion and friction angle) are considered as random variables (e.g., for saturated conditions) and the infinite slope model is used for the slope stability analysis[8,10]. When the soil retention curve parameters are also assumed to be random (e.g. for unsaturated conditions), analytical derivation of FS distribution is not tractable[8,10]. In this case, the First Order Second Moment (FOSM) method[14] is commonly used to estimate analytical approximations of the spatio-temporal FS statistics (i.e. mean and variance)[15,16,17,18], to finally fit a theoretical probability distribution for FS and estimate the spatio-temporal dynamics of probability of failure.

In order to systematically account for the parameter uncertainty, we propose a probabilistic approach for coupled distributed hydrological-stability models based on the FOSM method, which was implemented in the tRIBS-VEGGIE (*Triangulated Irregular Network (TIN)-based Real-time Integrated Basin Simulator - VEGetation Generator for Interactive Evolution*) - Landslide module[7]. The proposed methodology was applied to the Rio Mameyes Basin, located in the Luquillo Experimental Forest in Puerto Rico, where previous landslide analyses have been carried out. The main purpose of the application is to demonstrate the model capabilities and highlight further possible improvements.

2. Methodology

2.1. Model Overview

The tRIBS-VEGGIE-landslide module[7] is built upon the eco-hydrological model tRIBS-VEGGIE, which consists of a spatially distributed physically based hydrological model coupled to a model of plant physiology and spatial dynamics[19]. Basin hydrological response is simulated on an irregular spatial mesh which allows for the use of variable computational elements to describe the basin topography, by increasing the accuracy only in the most critical areas of the basin[20]. The model explicitly considers the spatial variability in land-surface descriptors and the corresponding moisture dynamics, stressing the role of topography in lateral redistribution. The infiltration module is responsible of the moisture fields computation and is based on a numerical approximation of the one dimensional Richards' equation[21]. The dynamics of each computational element are simulated separately, but spatial dependencies are introduced by considering the surface and subsurface moisture transfers among the elements along the direction of steepest descent, based upon the unsaturated hydraulic conductivity of the receiving cell. The soil retention and the unsaturated hydraulic conductivity are related to soil-moisture content through the Brooks and Corey[22] (BC) parameterization scheme[23], as a function of saturated hydraulic conductivity in the normal to the soil